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Damage Resistance of High Modulus Aramid Fiber Composites in Aircraft Applications

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IN RECENT YEARS, considerable progress has been made in the application of reinforced composites in aircraft structures. With this comes greater exposure to impact damage from the aircraft's operating environment which reflects a need to assess the damage resistance characteristics of composite materials.

The purpose of this paper is to develop a comparison of aramid, glass, and graphite fibers composites' mechanical property characteristics and the damage resistance of these reinforcing fibers.

Although there is no one accepted method of testing the damage resistance of composite materials, this paper will deal with a variety of analyses which describe the amount of energy absorbed through impact:

1. Ball drop impact on honeycomb face sheets.
2. Charpy impact (conventional and thin specimen).
3. Izod impact.
4. Fracture Toughness.

Through these analyses a better perspective on the in-service performance qualities of composite materials should become apparent.

MECHANICAL PROPERTIES OF UNIDIRECTIONAL LAMINA

ARAMID, GLASS, AND GRAPHITE—The specific reinforcing fibers included in this paper are:

1. Kevlar® 49 aramid fiber.
2. E-glass fiber.
3. High strength (HS) graphite fiber.
4. High modulus (HM) graphite fiber.

The aramid is a high modulus (19×10^6 psi) organic fiber which displays a linear tensile stress/strain curve to failure similar to the inorganic fibers, glass and graphite. (Fig. 1)

The combination of high tensile strength with its 0.053 pounds per in^3 density give the aramid fiber the highest specific tensile strength followed by the graphites and then E-glass. The graphite fibers have higher specific tensile moduli followed by aramid and then E-glass. (Fig. 2)

Comparison of mechanical properties of unidirectional lamina of aramid, glass, and graphite (Table 1) indicate the significant advantages in density, tensile strength and stiffness that aramid and graphite have over glass. Other lamina

ABSTRACT

Analyses of impact resistance are made for composites reinforced with fibers of high modulus aramid, glass, graphite, and graphite/high modulus aramid hybrids which indicate that the aramid fiber offers advantages over the other materials in thin laminate specimens when measured by Charpy, Izod, and ball drop impact tests while retaining some structural integrity. Use of the high modulus aramid fiber as a hybrid with graphite resulted in higher impact energy resistance than the all-graphite fiber composite.

The fracture characteristics of notched quasi-isotropic high modulus aramid, E-glass, and A-S graphite epoxy lamina and of notched fabric epoxy lamina of aramid and of glass are analyzed. Aramid showed the highest fracture resistance, followed by glass and graphite.
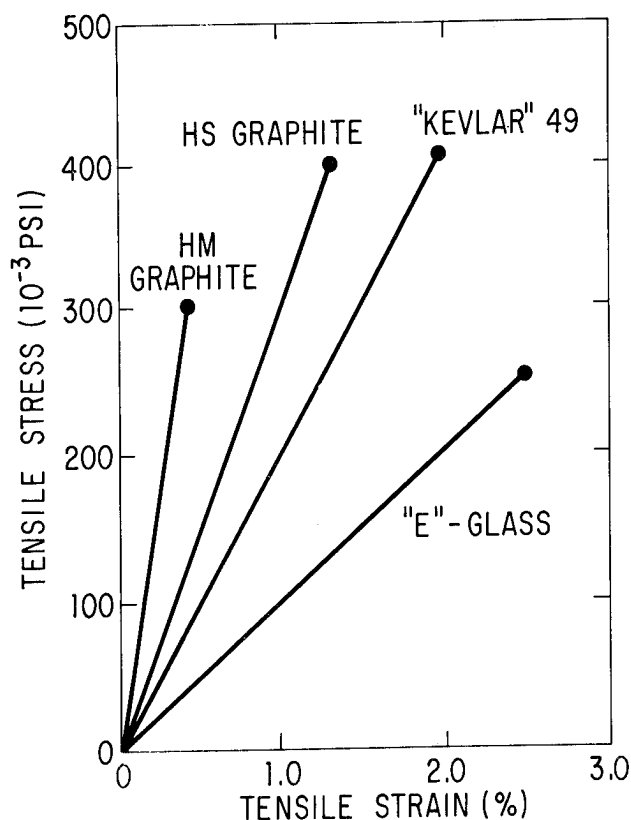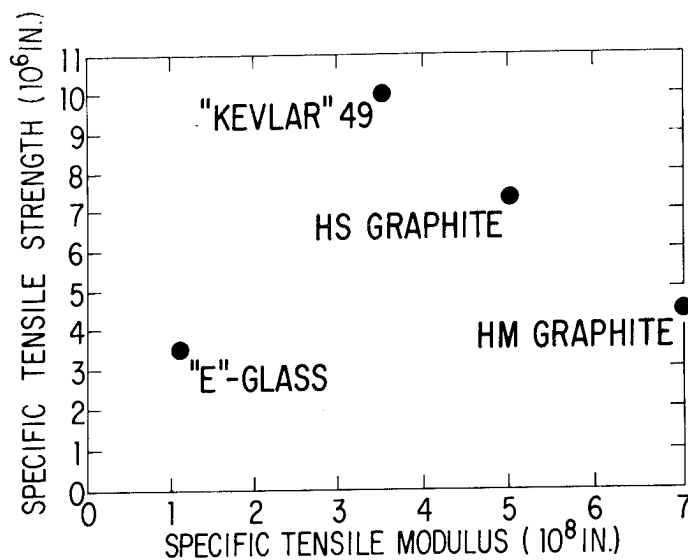
Fig. 1 — Tensile stress/strain curves

Fig. 2 — Specific tensile strength versus specific tensile modulus

properties, with the exception of aramid's compressive strength, are in good balance (1)*.

ARAMID/GRAPHITE HYBRIDS—The use of high modulus, high strength graphite fiber composites has enabled the achievement of new levels of improved performance and weight savings. However, these fibers have certain inherent properties, such as impact strength, which limit their range of application. Using composite materials incorporating more

*Numbers in parentheses designate References at end of paper.

than one type of fiber—hybrid composites—extends the range of material properties that can be obtained. The concept of hybridization involves the use of fibers with different, but complimentary, mechanical properties. Aramid fiber is an obvious choice for hybridization with graphite because aramid is a low density fiber and has a high strain to failure for improved impact resistance.

The average axial (0°) tensile, compressive, and short beam shear properties of unidirectional composites normalized to 60 V/O fiber and made up in ratios of fibers ranging from all graphite to all aramid are shown in Tables 2-3

The tensile strengths of the hybrid epoxy composites are plotted in Fig. 3 in comparison with the theoretical prediction. The tensile strengths are lower for the hybrid composites than for either of the individual fiber composites because the mixed fiber composites fail at the strain of the lower strain-to-failure fiber—in this case, the graphite at about 1% strain. The samples fall close to theory. The tensile modulus values are plotted in Fig. 4 and follow the rule of mixtures prediction. The interlaminar or short beam shear lengths are 8-13 ksi in almost all cases for the hybrids. Fig. 5 shows the typical axial compressive stress-strain curves for the all-aramid and all graphite/epoxy composites, while Fig. 6 shows the compressive 0.02% offset yield strength for the unidirectional aramid/graphite hybrid epoxy composites as a function of the amount of graphite. At a 50/50 aramid/graphite ratio, the aramid/T-300 and A-S blends gave a 56% improvement in compressive 0.02% offset yield over the all aramid composite, while the aramid/HM-S blends showed a 78% improvement. At a 25/75 aramid/graphite ratio, the aramid/HM-S and T-300 blends gave a 115-120% improvement in compressive yield, while the aramid/A-S blend showed a 94% improvement (2).
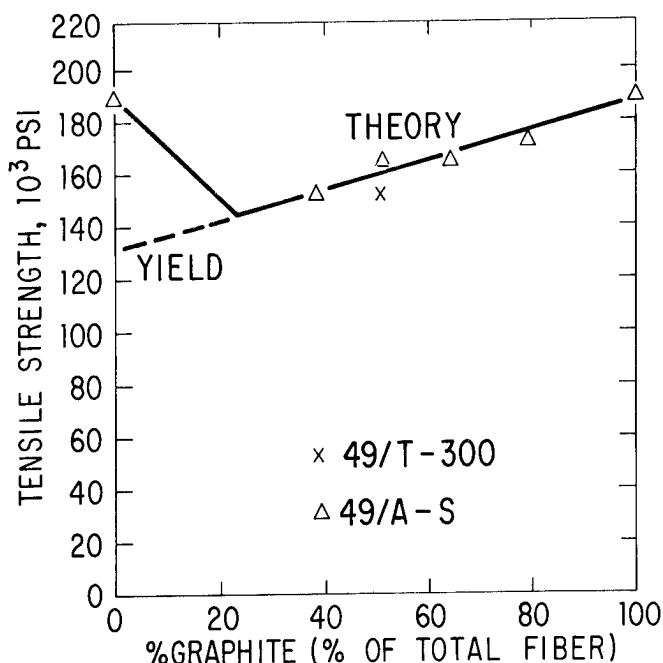

Fig. 3 — Tensile strength of Aramid/Graphite Unidirectional Hybrid Composites compared with theoretical prediction (60 V/O total fiber content)

Table 1 — Typical "Kevlar" 49, E-Glass, and HS-Graphite/Epoxy
Unidirectional Composite Properties

	E-Glass	Kevlar® 49	HS Graphite
Density, lb/in^3	0.075	0.050	0.055
Tensile Strength 0° (10^3 psi)	160	200	180
Compressive Strength 0° (10^3 psi)	85	40	160
Tensile Strength 90° (10^3 psi)	5.0	4.0	6.0
Compressive Strength 90° (10^3 psi)	20	20	20
In-Plane Shear Strength (10^3 psi)	9	6.4	9.0
Interlaminar Shear Strength (10^3 psi)	12	14	14
Poisson's Ratio	0.30	0.34	0.25
Tens. and Comp. Modulus 0° (10^6 psi)	5.7	12	19
Tens. and Comp. Modulus 90° (10^6 psi)	1.3	0.8	0.9
In-Plane Shear Modulus (10^6 psi)	0.5	0.3	0.7
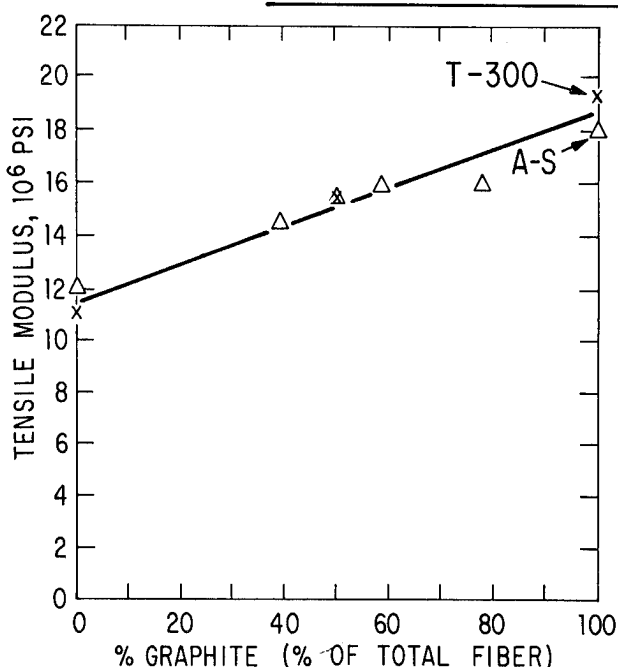
Fig. 4 — Tensile modulus of Unidirectional Kevlar® 49/Graphite Hybrid Composites (60 V/O total fiber content)

Fig. 5 — Compressive stress-strain curves for Unidirectional 60 V/O Kevlar® 49 and "Thornel" 300 Graphite Composites

DAMAGE RESISTANCE

IMPACT STRENGTH — To determine the impact energy-absorbing characteristics of aramid, glass, graphite, and aramid/graphite hybrid reinforced composites, the results from the ball drop impact test, the instrumented Charpy impact test, and the Izod impact test were analyzed.

Ball Drop Impact — Face sheets of aramid or glass fabricated from "Hysol" 9704 epoxy prepreg on a 0.325 in thick with 3/16 in cell size Nomex® aramid honeycomb core weighing 5.8 lb/ft^3 were impacted by a falling 2 lb, 3/4 in diameter spherical-nosed missile on a ball-drop impact tester. The variables analyzed were the fabric weave design and the number of plies used in the construction. The aramid fabric designs investigated included: Style 181, a 50-end by 50-pick (380 denier), 8-harness satin construction; Style 281, a 17 × 17
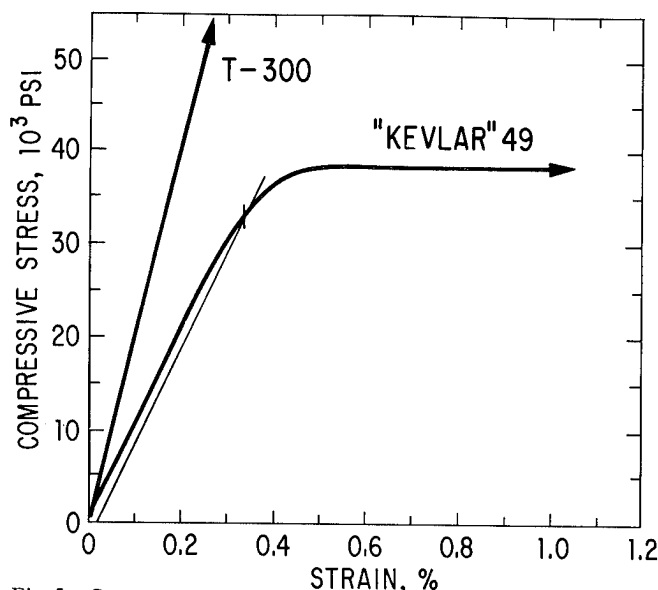
(1140 denier) plain weave; and Style 328, a 17 × 17 (1420 denier) plain weave. Both the Style 181 and 281 have the same basis weight (5 oz/yd^2) and the same thickness (10 mils), while the Style 328 has a 6.8 oz/yd^2 weight and 13 mil thickness. Glass fabric weaves analyzed were Style 181 (fabric volume analog of aramid Style 181) and Style 2542 (best fabric volume analog of aramid Style 281).

The ball-drop results (Table 4 and Fig. 7) indicate that the aramid weave design has a significant effect on impact resistance. For sandwich panels comprised of single-ply face sheets, impact resistance is essentially doubled by substituting heavy denier, Style 281 or 328, for Style 181. For glass fabric reinforced face sheets, however, impact resistances for Styles 181 and 2542 are essentially equal. Also, it is indicated by these results that impact strength is a function of the number of face sheet fabric plies, and that the reduction of impact resistance per ply appears to be less for glass fabrics than for aramid (3).

Table 2 — Mechanical Properties of Unidirectional "Kevlar"
49/AS-Graphite Hybrid Composites

FIBER RATIO

"Kevlar" 49 %	0	20	40	50	60	100
A-S Graphite %	100	80	60	50	40	0

STRENGTH (KSI)

0° Tensile	190	17?	150	162	145	190
90° Tensile	10	6.8	6.7	6.0	2.8	?
0° Compression	150	131	112	116	110	40
0° Flexure	210	201	191	204	178	100
90° Flexure	12.0	18.6	20.6	16.7	13.8	5.6
Short Beam Shear	16.0	13.5	13.6	12.8	12.2	10

MODULUS (MSI)

0° Tensile	18.0	15.6	15.7	15.2	13.6	12
90° Tensile	1.2	1.12	1.01	1.18	1.07	0.8
0° Compression	18	11.2	10.4	11.6	10.6	10.6
0° Flexure	16.5	13.0	12.3	13.5	12.6	10.8
90° Flexure		2.46	2.20	2.70	2.10	

Table 3 — Tensile, Compressive, and Shear Properties of Unidirectional
"Kevlar" 49 and Graphite Composites Normalized to 60 V/O Fiber

Fiber	V/O Fiber	Resin	Tension			Compression				Shear SBS 10^3psi
			Ult. ksi	Mod. 10^6psi	Strain to Failure %	Ult. ksi	Prop. Limit ksi	0.02% Offset Yield ksi	Mod. 10^6psi	
"Kevlar" 49	60	PR-286	200	11.0	1.80	40	30	32	10.5	8.7
HM-S Graphite	60	PR-286	--	--	--	87	52	84	24.0	9.0
HM-S Graphite	60	PR-286	110	28.0	0.44	100	--	100	28	9.0
A-S Graphite	60	PR-286	147	15.2	0.97	160	54	75	15.9	15.6
A-S Graphite	60	PR-286	--	--	--	150	--	--	18	16.0
"Thornel" 300	60	BP-907	185	19.2	0.96	109	88	109	20.6	12.6
"Kevlar" 49 HM-S	12.2 47.8	PR-286	--	--	--	71	46	70	22.4	10.2
"Kevlar" 49 HM-S	23.?	PR-286	--	--	--	71	38	65	20.2	9.7
"Kevlar" 49 HM-S Graphite	20.9 39.1	PR-286	61.2	24.5	0.25	--	--	--	--	--
"Kevlar" 49 A-S	16.0 44.0	PR-286	--	--	--	98	49	61	12.4	10.6
"Kevlar" 49 A-S	28.8 31.2	PR-286	--	--	--	94	40	50	12.3	10.7
"Kevlar" 49 A-S Graphite	25.1 33.9	PR-286	143	14.1	1.01	--	--	--	--	--
"Kevlar" 49 T-300	13.1 46.9	BP-907	--	--	--	87	51	76	16.5	10.9
"Kevlar" 49 T-300	29.3 30.7	BP-907	--	--	--	76	38	54	13.1	8.0
"Kevlar" 49 T-300	29.4 30.6	BP-907	153	15.5	0.99	--	--	--	--	--

Charpy Impact — The instrumented Charpy testing machine was used to study the impact behavior of the reinforced composite materials. The output of the instrumented Charpy provides a load time history of the impacted specimen and allows differentiation between the energy absorbed in the specimen during initiation of the fracture (energy absorbed up to the peak load) and the energy absorbed during the propagation of that fracture (energy absorbed after the peak load). Materials with low propagation energy tend to be more brittle and fail catastrophically.
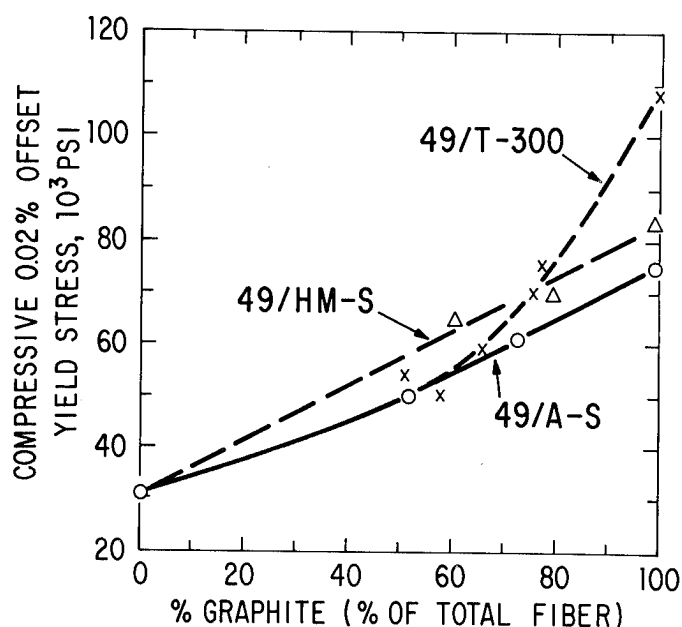
Fig. 6 — Compressive 0.02% offset yield strength of Unidirectional Kevlar® 49/Graphite Hybrid Composites (60 V/O total fiber content)

The standard Charpy test uses a 0.4 in thick specimen for obtaining impact energy. This sample thickness is not typical of many of the thinner composite skins used in aircraft. Therefore, in addition to the standard specimen, thin composite specimens were examined.

In Fig. 8 are representations of the load-time and cumulative energy-time traces of the instrumented Charpy test of a 0.40 in unidirectional glass/epoxy composite. The areas of initiation energy and propagation energy are observed. In Fig. 9, a thin (0.14 in) glass/epoxy specimen is examined. Here there is very little energy absorbed during the propagation phase indicating the catastrophic nature of the specimen failure. The corresponding tests of thick and thin specimens of aramid/epoxy are shown in Figs. 10-11, respectively. The load-time traces indicate significant propagation energies in both the thick and thin sample which are the result of the specimens' retaining some structural integrity following peak load failure (4).

The Charpy and Izod impact tests of unidirectional hybrid composites which indicate energy absorbing capabilities are shown in Figs. 12-13, respectively, with results tabulated in Table 5. These results show substantial improvement in
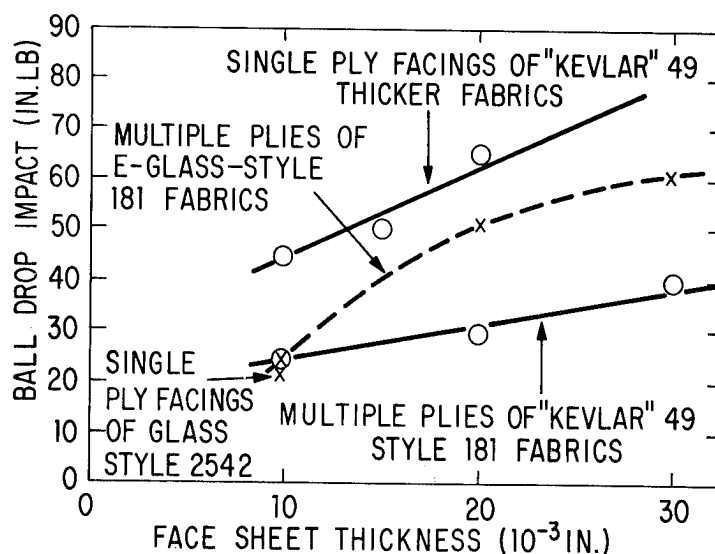

Fig. 7 — Impact strength of Kevlar® 49 and E-Glass Fabric/Hysol 9704 Epoxy Faced "Nomex" Honeycomb Core Sandwich Panels

Table 4 — Impact Resistance of Honeycomb Sandwich Panels Faced with Glass and "Kevlar" 49 Fabric Epoxy Laminates

Fabric	Weave	Ply Thickness Mils	Impact Resistance (In-Lb)		
			One-Ply	Two-Plies	Three-Plies
Style 181 "Kevlar" 49	8-HS	10	25	30	40
Style 181 E-Glass	8-HS	10	25	50	60
Style 281 "Kevlar" 49	Plain	10	45	50	60
Style 2542 E-Glass	Plain	10	22	--	--
Style 328 "Kevlar" 49	Plain	13	50	55	--
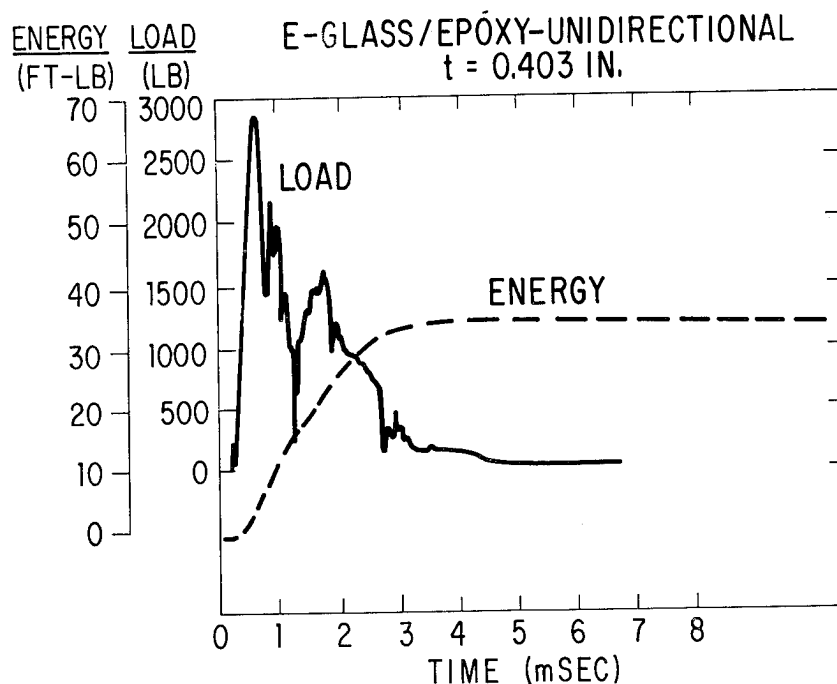
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ENERGY LOAD
(FT-LB) (LB)

E-GLASS/EPOXY-UNIDIRECTIONAL
t = 0.403 IN.

LOAD

ENERGY

TIME (mSEC)

Fig. 8 — Load history of Charpy Impact Test E-Glass/Epoxy Unidirectional t = 0.403 in

ENERGY LOAD
(FT-LB) (LB)

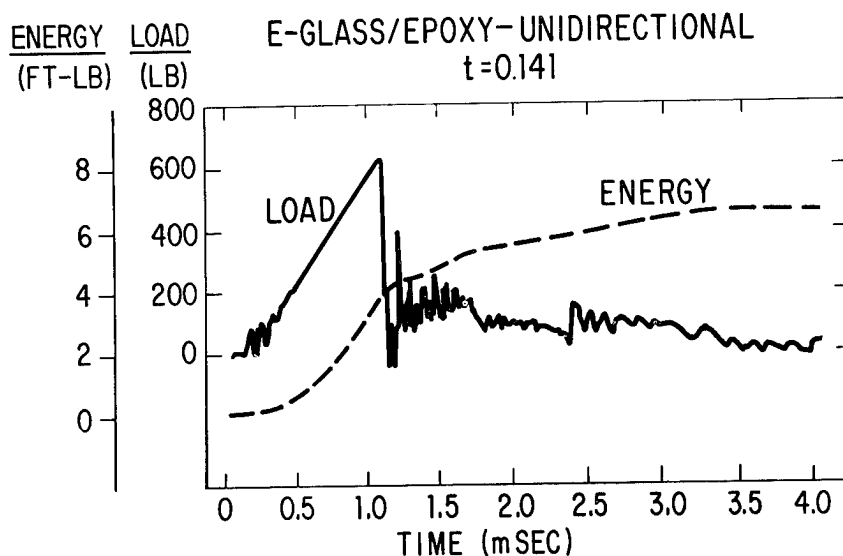E-GLASS/EPOXY-UNIDIRECTIONAL
t=0.141

LOAD

ENERGY

TIME (mSEC)

Fig. 9 — Load history of Charpy Impact Test E-Glass/Epoxy Unidirectional t = 0.141

impact strength over all-graphite composites with the addition of aramid. In the Charpy test the all-"Thornel" 300 composite has 5.6X the impact strength over an all-HM-S graphite composite, and a hybrid composition of 50/50 aramid/HM-S can increase the strength 7X over the all-HM-S composite. A similar amount of aramid in a T-300 composite increased the Charpy impact strength by 50%, and aramid in an A-S composite increased impact strength by 100% over respective all-graphite controls.

More dramatic improvements in impact performance over all-graphite are shown in Fig. 13 where hybrids were tested by the Izod (cantilever beam) test, illustrating the fact that im-

pact test method can dramatically affect the relative performance of materials. With the all-graphite composites, the T-300 was substantially better than Type A-S or HM-S graphite. In Fig. 13, the slopes of the impact strength curves are reasonably constant for all hybrid systems. At any composition level, the highest impact strengths are seen with aramid/T-300 followed by aramid/A-S and then by aramid/HM-S. At the 50/50 aramid/graphite ratio, the aramid/T-300 composite had 125% higher impact strength than all-T-300 composites, and a 19X increase over the all HM-S composite.

The impact strengths of all aramid composites are misleading since they did not fracture completely on testing and still
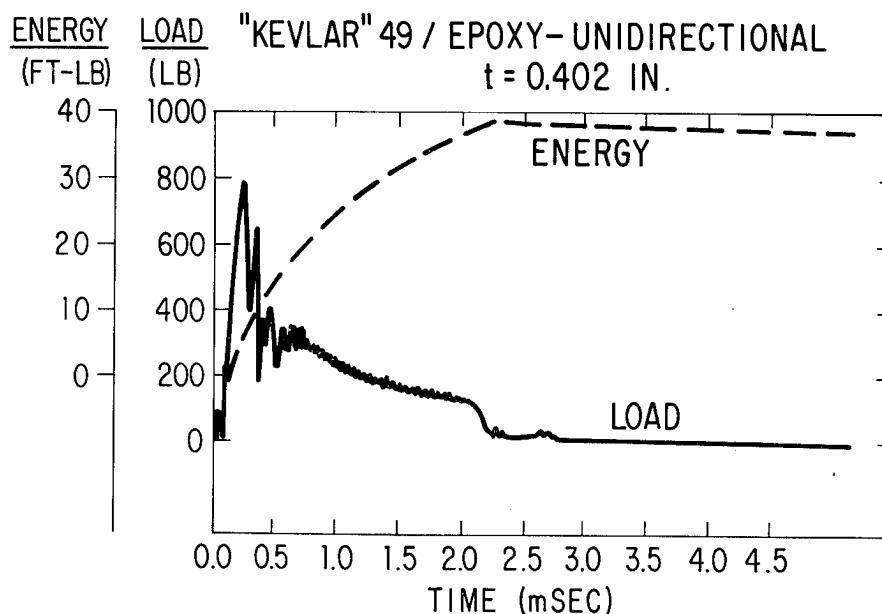
ENERGY LOAD **"KEVLAR" 49 / EPOXY- UNIDIRECTIONAL**
(FT-LB) (LB) **t = 0.402 IN.**

Fig. 10 — Load history of Charpy Impact Test "Kevlar" 49/Epoxy Uni-
directional t = 0.402 in

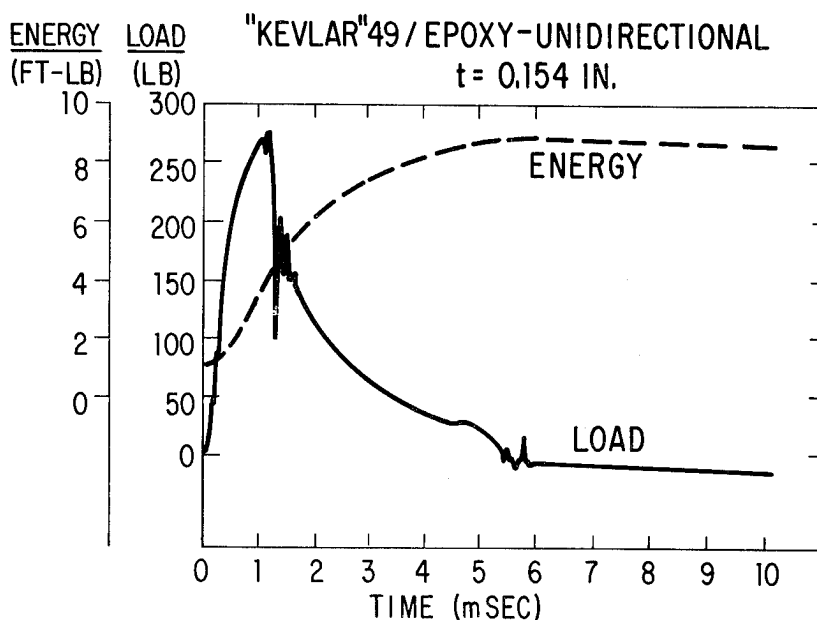ENERGY LOAD **"KEVLAR"49 / EPOXY-UNIDIRECTIONAL**
(FT-LB) (LB) **t = 0.154 IN.**

Fig. 11 — Load history of Charpy Impact Test "Kevlar" 49/Epoxy Uni-
directional t = 0.154 in

have significant amounts of energy absorbing capability after the tests. Thus, these values should be considered as lower bounds on the true all-aramid impact strength (2).

The high impact strength of the aramid composite combined with its low density and good mechanical properties make it an attractive candidate for such aircraft applications as interior panels, cargo bay liners, flooring, debris shields, fairings, radomes, doors, covers, and engine nacelles.

NOTCH FRACTURE CHARACTERISTICS—The influences of notch length on fracture characteristics of unidirectional, quasi-isotropic (0/90/±45) aramid, E-glass, and A-S graphite/epoxy laminates were analyzed. The characteristics of fabric (Style 181) aramid/epoxy and E-glass/epoxy laminates were

also analyzed. Resins used for the quasi-isotropic samples included PR-286 (3-M) with aramid and graphite while E-glass had 1002 (3-M) resin. The fabrics of aramid and glass used F-155 (Hexcel) resin.

The coupon gage dimensions were 2-1/2 X 10 in for the notched specimens and 1 X 5 in for the unnotched specimens. Sharp center notches of 1/4, 1/2, and 1 in were tested. Notches were machined to a length 1/8 in less than final. The notch was extended 1/16 in at each end with a 6-mil jeweler's saw (Fig. 14).

Variation of the net stresses with notch length are shown in Fig. 15 and Tables 6-7. Corresponding net notched specimen stress of the quasi-isotropic aramid composites are 60-70%

Table 5 — Impact Properties of Unidirectional "Kevlar" 49 and Graphite Composites Normalized to 60 V/O Fiber

Fiber	V/O Fiber	Resin	Impact Charpy ft-lb/in^2	Impact Izod ft-lb/in^2
"Kevlar" 49	60	PR-286	150	75
HM-S Graphite	60	PR-286	11.0	3.6
A-S Graphite	60	PR-286	48	15.5
"Thornel" 300	60	BP-907	62.6	31.9
"Kevlar" 49 HM-S	12.2 47.8	PR-286	37.3	28.7
"Kevlar" 49 HM-S	23.4 36.7	PR-286	54	39
"Kevlar" 49 A-S	16.0 44.0	PR-286	110	37
"Kevlar" 49 A-S	28.8 31.2	PR-286	94	57
"Kevlar" 49 T-300	13.1 46.9	BP-907	61	52
"Kevlar" 49 T-300	29.3 30.7	BP-907	88	68

Table 6 — Strength of Notched "Kevlar" 49/Epoxy and E-Glass/Epoxy (0/90/±45) Laminates made from 181-Style Fabric

Nominal Crack Length 2a (in.)	Nominal Specimen Width 2b (in.)	"Kevlar" 49/Epoxy (E = 3.47 x 10^6 psi) Gross Stress σ_g (ksi)	Net Stress σ_n (ksi)	E-Glass/Epoxy (E = 2.45 x 10^6 psi) Gross Stress σ_g (ksi)	Net Stress σ_n (ksi)	Graphite/Epoxy (E = 5.65 x 10^6 psi) Gross Stress σ_g (ksi)	Net Stress σ_n (ksi)
0	1	57.1	57.1	41.6	41.6	61.9	61.9
1/4	2 1/2	42.2	47.0	24.7	27.6	16.81	22.6
1/2	2 1/2	35.4	44.3	19.9	25.1		
1	2 1/2	25.5	43.1	14.7	24.6		

Table 7 — Strength of Notched "Kevlar" 49/Epoxy, E-Glass/Epoxy, and Graphite/Epoxy (0/90/±45) Laminates Made from Unidirectional Tape

Nominal Crack Length 2a (in.)	Nominal Specimen Width 2b (in.)	"Kevlar" 49/Epoxy (E = 3.23 x 10^6 psi) Gross Stress σ_g (ksi)	Net Stress σ_n (ksi)	E-Glass/Epoxy (E = 2.92 x 10^6 psi) Gross Stress σ_g (ksi)	Net Stress σ_n (ksi)
0	1	54.2	54.2	40.2	40.2
1/4	2 1/2	37.1	41.4	24.0	26.7
1/2	2 1/2	28.5	36.2	17.6	22.0
1	1	30.1	40.3	13.0	21.7
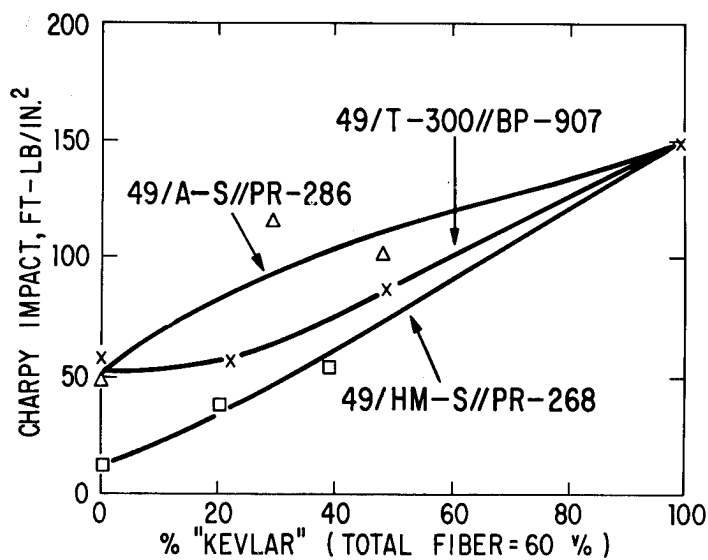
Fig. 12 — Charpy impact strength of Unidirectional Kevlar® 49 Hybrid Composites
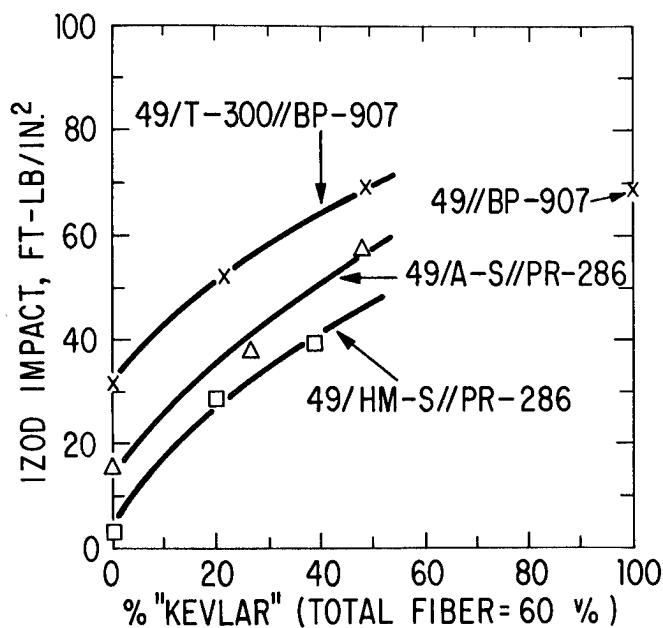

Fig. 14 — Notched fracture specimen

Fig. 13 — Izod impact strength of Unidirectional Kevlar® 49 Composites

higher than the E-glass composites and 108% higher than the graphite composite, while this same stress of the fabric aramid composites is 55-65% higher than the fabric E-glass composites (5).

The high notch fracture strength characteristic of aramid composites reduces the opportunity for crack propagation around stress concentrations such as bolt holes, notches, corners, and holes resulting from impact damage.

Fig. 15 — Net failure stress versus notch length for "Kevlar" 49, E-Glass, and Graphite Quasi-Isotropic Laminates

CONCLUSIONS

As a result of this analysis of mechanical and damage resistance properties of aramid, glass, graphite, and aramid/graphite hybrid reinforced composites, these conclusions are drawn:

1. Damage resistance of aramid reinforced composites is shown to be superior to glass and graphite composites and attractive for many aircraft composite applications based on energy absorption during ball drop impact, Charpy impact, Izod impact, and notch fracture strength tests.

2. The impact resistance of graphite composites can be substantially improved via hybridization with aramid with only moderate change in mechanical properties while maintaining low weight for aircraft structures.

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